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DIFFERENTIAL ENERGY SPECTRA OF LOW ENERGY (< 8.5 MeV PER NUCLEON) HEAVY COSMIC RAYS DURING SOLAR QUIET TIMES[x]

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Abstract Carbon, oxygen and heavier nuclei have been observed below 8.5 MeV per nucleon during solar quiet times. We find that the C/O abundance ratio is 0.50 ± 0.15, and the differential energy spectra below 1 MeV have the form $KE^{-4.9 \pm 0.3}$. We infer from this ratio that most of these particles are likely to be of solar origin.

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Although extensive satellite and balloon measurements[1-5] have provided abundant information over most of the present solar cycle about the modulated galactic cosmic rays above roughly 15 MeV per nucleon, the extension of observations during solar quiet times below this energy has been limited to protons and α-particles[6,7]. The continuous presence of low energy protons and helium nuclei during solar quiet times was first established by Fan et al.[6,8] who also found unexpected upturns in the spectra below about 20 MeV and surprisingly little variation in the flux or spectral shapes during quiet periods from 1964 to 1967. Kinsey's[7] careful analysis of data from the Goddard dE/dx vs. E experiments on IMPs 3 and 4 while revealing a continuous presence of protons and alpha particles down to 5 MeV per nucleon showed substantial variability of these low energy components over the time periods May 1967 to August 1968. He concluded that during most of the time period particles below about 10 MeV nucleon were substantially of solar origin.

In this letter we present for the first time measurements of low energy ($<$ 8.5 MeV per nucleon) heavy cosmic rays in interplanetary space during relatively quiet time periods. The data were obtained in October 1972 using a newly designed Ultra low Energy Telescope (ULET) on board the Explorer 47 satellite which was launched on September 22, 1972 into a nearly circular, 240,000 km apogee orbit. ULET operated successfully until 19 November, 1972 when the thin window of the proportional counter ruptured. Because of this only a limited amount of quiet time data could be collected. In this letter we restrict ourselves to particles with a nuclear charge $Z \geq 6$.

The detector system[9] makes use of the dE/dx vs. E method for particle identification and energy determination. To extend to 200 KeV/nucleon the energy range over which two parameter analysis can be made we use a thin window proportional counter, referred to as D1, for the "dE/dx" measurement and a conventional, fully depleted, 700 um thick surface barrier silicon detector, called D2, for the "E" determination. A plastic scintillator cylindrical cup anticoincidence detector, S, which surrounds D1 and D2 is used to reject background and penetrating particles. The total thickness of material in front of the solid state detector is 330 $\mu g/cm^2$, 140 $\mu g/cm^2$ of which is due to the isobutane counter gas. The geometrical factor of the telescope is 1.0 cm^2 sr. To obtain preferential analysis of heavy particle we set the energy thresholds at 450 KeV for the proportional counter and at 1 MeV for the solid state detector which sets a limit on the upper energy for analysis of carbon and oxygen at 4 and 8.5 MeV per nucleon respectively. We should note that the ULET telescope scans in the ecliptic plane thus allowing us to obtain angular distribution measurements.

Analysis of an event takes place only when the proportional counter D1 is triggered in coincidence with the solid state detector D2 in absence of pulses from the anticoincidence scintillator S. The pulse heights of the D1 and of the D2 signals together with the value of the azimuth angle of the telescope with respect to the sun-satellite line are transmitted at a maximum rate of 11.7 events per minute. In addition, we record the counting rate $D1D2\bar{S}$ corresponding to the true rate of all events which satisfy the coincidence logic.

Only data accumulated during two time periods when D1D2S was at its lowest level (0.0013 counts/sec.) were used in the present analysis (1 to 11 and 19 to 22 October, 1972). In addition, we examined the 120 - 160 KeV proton rate of the University of Maryland Experiment[10] on the same spacecraft and excluded times when this rate was significantly above background. The satellite was outside the bow-shock for all but 60 of 315 hours of the quiet time periods; hence these measurements are representative of conditions in interplanetary space. As a further indication of solar quiet conditions we note that the K_p index was generally substantially less than 3 and never exceeded 4.

The counting rate D1D2S remained constant in each period and had the same average value, within statistical error, in both periods indicating that during these quiet time periods the particle flux remained steady.

In Fig. 1 we show the D1 vs. D2 pulse height distribution for the 78 events recorded during 315 hours. The dashed curves represent the locations of respective tracks for C, O and Ne which were obtained from an inflight calibration provided by solar particles during the October 29, 1972 flare[11].

The angular distribution in the ecliptic plane of all events of Fig. 1 is presented in Fig. 2(a). The polar plot, which shows the number of particles in each of eight angular sectors, indicates a maximum in sector 4 or in a direction roughly 20° west of the sun-earth line. From these data we find an anisotropy of (25 ± 8)% with the flow of particles directed away from and 22° west of the sun.

The differential energy spectra for carbon and oxygen derived from data of Fig. 1 are given in Fig. 2(b). Error bars are one standard deviation limits resulting from counting statistics. We note that the low energy portions of the C and O spectra have steep negative slopes and may be represented by a dependence on kinetic energy E of the form $dJ/dE = KE^{-4.9\pm0.3}$, and that the oxygen spectrum has a significant hump between 2 and 8.5 MeV per nucleon. Whether or not a similar feature exists in the carbon spectrum cannot be determined at this time because we do not analyse carbon above 4 MeV per nucleon. At energies below 1 MeV per nucleon the average C/O abundance ratio is 0.5 ± 0.15. Because particles heavier than oxygen cannot be uniquely identified[11] below 500 KeV per nucleon the flux points labeled "Si" and "Fe" in Fig. 2(b) were computed under the respective assumptions that events above the oxygen track in Fig. 1 are all either silicon or all iron nuclei.

Our data clearly indicate that during solar quiet times a steady flux of very low energy heavy particles is present in interplanetary space, and that the observed differential energy spectra are qualitatively similar to the quiet time spectra of protons and helium nuclei reported by Fan et al.[6,8] and Kinsey[7].

It is not easy from these observations alone to decide on the likely origin of the steady flux of low energy particles. For energies below about 1 MeV per nucleon we favor a solar origin primarily because our observed value of 0.5 for the C/O ratio agrees with similar ratios found in solar cosmic rays and the photsphere[12], but is quite different from the C/O value of 1 to

1.3 for galactic cosmic rays[5]. Furthermore, we note the similarity between these steep quiet time spectra and commonly observed spectra of solar flare particles[11-13]. The anisotropy we observe also suggests that these nuclei come from the sun. We note, however, that low energy galactic particles under special conditions can also exhibit anisotropies directed away from the sun[14].

A surprising feature of our measurements is the increased oxygen flux between 2 and 8.5 MeV per nucleon which is a factor of 40 larger than the maximum galactic cosmic ray flux at 35 MeV per nucleon observed in 1965[3]. We find it difficult to interpret this feature of the spectrum but note that it may be related to similar anomalies found recently in the quiet time helium spectrum[15]. Further and more extensive observations during quiet times in this energy range will be required before we understand more fully the nature of the observed steady flux of low energy particles.

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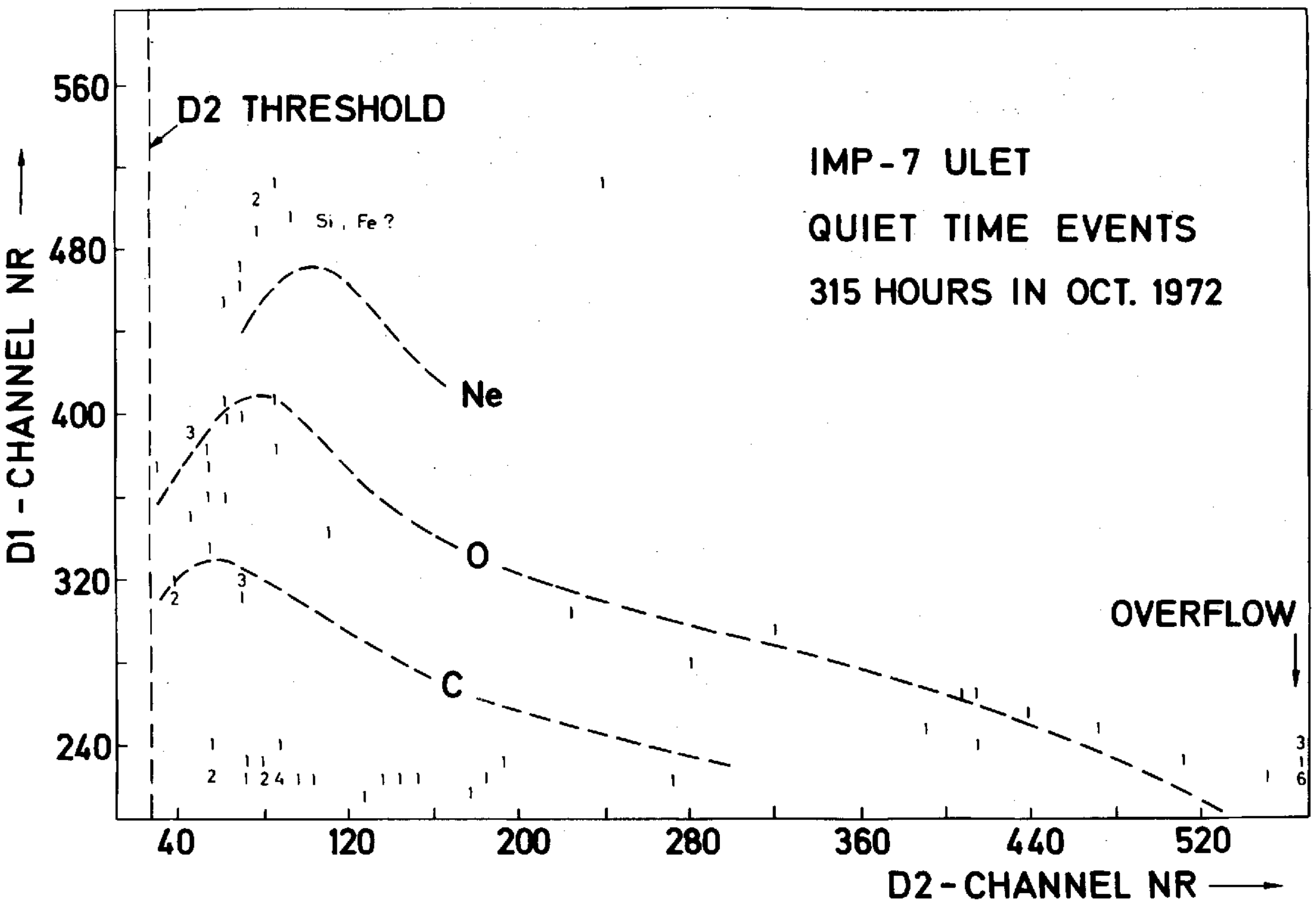
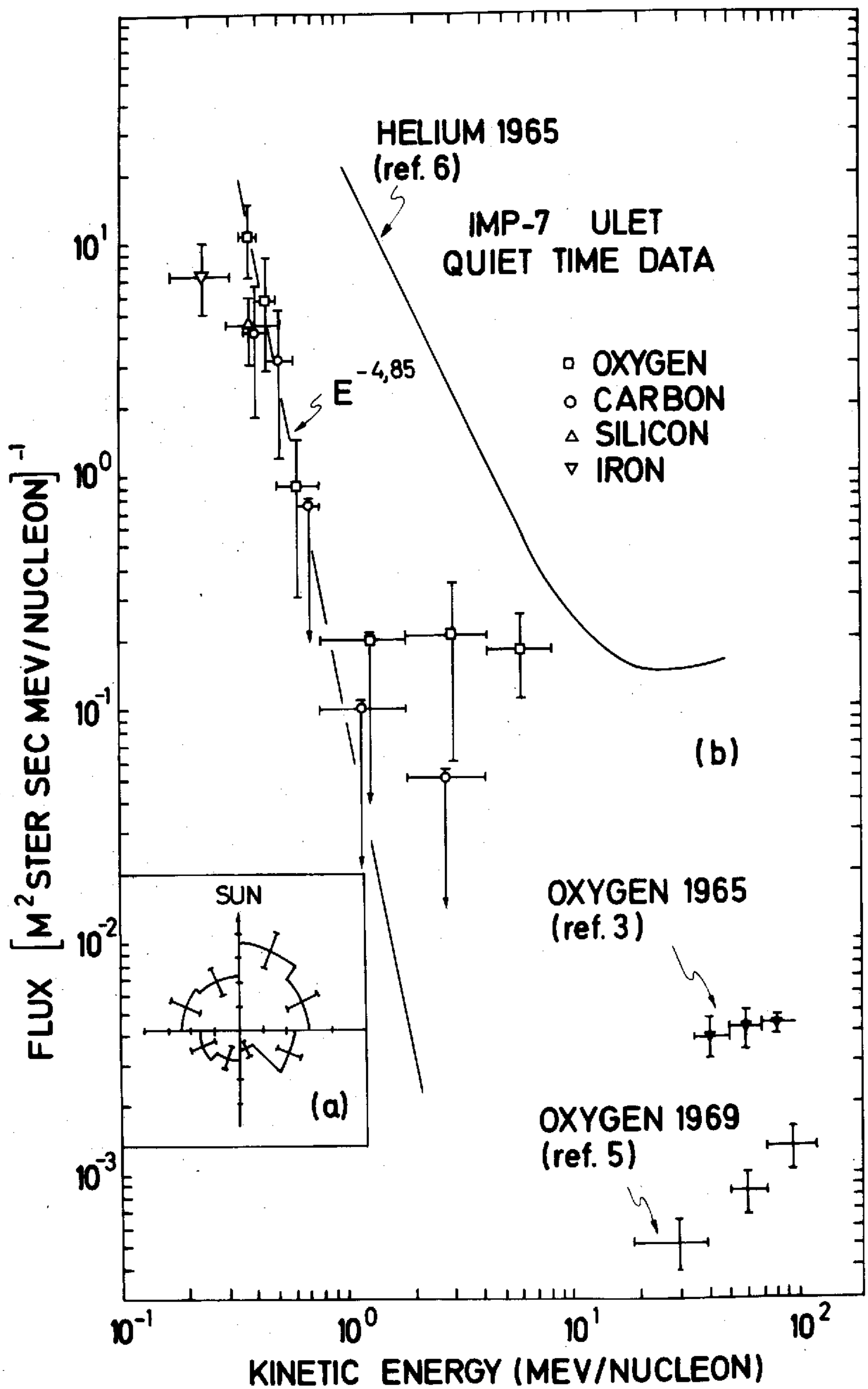
Figure Captions

Fig. 1. Two dimensional dE/dx versus E pulse height analysis data matrix showing the distribution of events recorded in proportional counter D1 and solid state detector D2 during solar quiet times in October 1972. Dashed curves represent track positions for C, O and Ne derived from solar particle data of 29 October 1972. Note that below D2 channel 100 (800 KeV per nucleon) one sees an accumulation of C, O and possibly N as well as particles heavier than oxygen, possibly Si and/or Fe. Around the oxygen track there is a significant reduction of particles between D2 channels 100 and 380 with a more abundant population starting above channel 380 or 4 MeV per nucleon.

Fig. 2. (a) Polar plot of the pulse height analysis data from Fig. 1 representing the angular distribution of the arrival direction of particles in the ecliptic plane.
(b) Differential energy spectra of oxygen and carbon nuclei derived from data shown in Fig. 1. Also shown are the flux values for nuclei heavier than oxygen computed under the assumption that (i) all these nuclei are silicon or (ii) all these particles are iron. For comparison we show the low energy helium spectrum (reference 6) as well as the galactic oxygen spectrum during solar minimum in 1965 (reference 3) and during 1968 (reference 5). Note that the C and O spectra are considerably steeper at low

energies than the helium spectrum and that the low energy upturn for oxygen is at around 1 MeV as opposed to about 20 MeV for helium.


D2 THRESHOLD
IMP-7 ULET
QUIET TIME EVENTS
315 HOURS IN OCT. 1972
Si , Fe ?
Ne
O
C
OVERFLOW
560
480
400
320
240
40
120
200
280
360
440
520
D1 - CHANNEL NR
D2 - CHANNEL NR


HELIUM 1965
(ref. 6)
IMP-7 ULET
QUIET TIME DATA
OXYGEN
CARBON
SILICON
IRON
E^-4,85
(b)
SUN
(a)
OXYGEN 1965
(ref. 3)
OXYGEN 1969
(ref. 5)
FLUX [M^2 STER SEC MEV/NUCLEON]^-1
KINETIC ENERGY (MEV/NUCLEON)
10^-3
10^-2
10^-1
10^0
10^1
10^2